A SEARCH FOR VERY HIGH ENERGY NEUTRINOS FROM ACTIVE GALACTIC NUCLEI

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ABSTRACT

We report the results of a search for neutrino-induced particle cascades using a deep ocean water Čerenkov detector. The effective mass of the detector, a string of seven 40 cm diameter photomultipliers (PMT) at 5.2 m spacing, is found through simulation analysis to be surprisingly large: greater than 10^6 tons of water at incident neutrino energies of 10^6 GeV. We find no evidence for neutrino-induced cascades in 18.6 hours of observation. Although the limit implied by this observation is the strongest yet for predictions of active galatic nuclei (AGN) neutrinos at energies above 100 TeV, perhaps the more intriguing result is that the power of these techniques can be exploited to test these AGN models in a relatively short time.

INTRODUCTION AND MOTIVATION

The idea behind our measurement of the neutrino flux is in essence, the same as extensive air shower (EAS) detectors, except in the ocean. Due to the optical properties of the deep ocean and the fact that water is $\sim 10^3$ more dense than the atmosphere, detector livetimes can accrue at a rate of $\sim$ kiloton-years (kty) *per day*.

We have re-analyzed data taken in November 1987 with respect to the optical properties of the deep ocean and used the results in our monte carlo. We then searched the data for the presence of cascades. In the following we present only the results of our analysis, the details of which can be found in Bolesta et al. (1997).

EFFECTIVE MASS FOR CASCADE DETECTION
Background Reduction

According to the models of Bierman (1992), Szabo and Protheroe (1994), Stecker and Salomon (1995), Protheroe (1996), we determined an *a priori* selection criterion for AGN neutrino-induced cascades based on our simulations: the event must produce ≥ 5 photoelectrons (PE) per PMT, for 6 out of 7 PMTs. After detailed simulations of detector response and all backgrounds, this cut was found to reject $\geq 90\%$ of the atmospheric muons, while still accepting $\sim 70\%$ of all of the cascades. Thus we maintained this selection criterion throughout the analysis.

Effective Mass Determination

The effective mass is calculated by taking the ratio of detected to generated monte carlo events as a function of the radial distance from the detector, and integrating it out to the edge of the generation volume. This estimate is shown in Figure 1. The effective mass exceeds 10 Mtons at the energy of the W resonance (Glashow, 1960), and is of order 2 Mtons at 100 TeV. At the highest energies, it approaches 200 Mtons, or 20% of a cubic kilometer of water.

RESULTS

Data Selection

To establish a pure sample of well-constrained muon events to act as a standard against which we can compare possible cascade candidates, we cut events which had less than 6 PMTs above the 1.6 PE threshold to reduce noise contamination. The remaining events constituted our parent sample of what is expected to be mostly muon events with a possible sub-population of cascade events.

Fig. 1: *Effective mass of the SPS for cascade detection as a function of cascade energy.*

Muon fitting

The muon track parameters were estimated from the data using maximum likelihood.The cumulative probability curve for this likelihood function was estimated by a Monte Carlo integration, and fits which fell outside of $\sim 2\sigma$ ($\sim 4\%$ probability) were excluded to avoid contamination from events that contained pre-pulse, bremsstrahlung, or bioluminescence activity. The fitting efficiency after this cut was $\sim 70\%$.

For our observation, the Monte Carlo estimate predicts that 8.8% of atmospheric muons which pass the 1.6 PE cut should also pass the 5 PE cut, corresponding to 18.7 events. We observed 17, consistent with no AGN neutrino cascade events present. All of the 17 events can be fit to parameters consistent with atmospheric muons.

Testing for possible cascades

To provide an independent test for the presence of cascades in the high–PE sample, we used a cascade likelihood fitting routine similar to that used to fit the muon track parameters applied both to the entire probable muon event parent sample, and to the subsample of those events above the 5 PE threshold.

The results of fitting both the parent muon sample and the high PE subsample to the cascade hypothesis are shown in Figure 2, where the cascade vertex angular distribution of $(1 - cos\ \theta_V)$ is plotted for both samples. The plot shows that the cascade fits of the parent muon sample (solid line) favor a range of zenith angles clustered around the muon Čerenkov angle for vertical tracks. The high PE distribution (hatched) shows no deviation from the parent distribution. Monte Carlo analysis of the fitting errors shows that the standard deviation for these fits in $cos\ \theta$ is 0.17. Thus both samples appear to be dominated by nearly vertical muon events, consistent with expectations. For comparison, we have also fitted a set of simulated atmospheric muon events (dotted histogram) and these show a distribution consistent with the
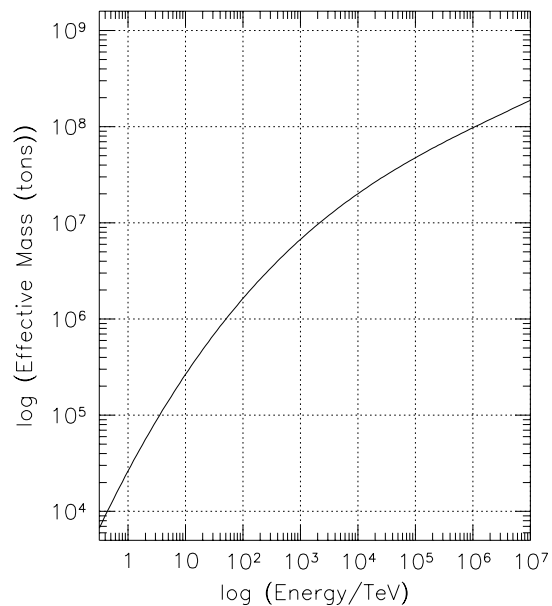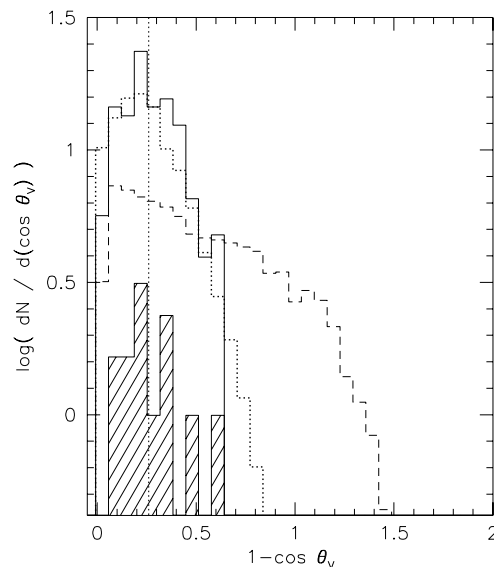

Fig. 2: *Angular distribution of events after fitting to a cascade hypothesis. The vertical dotted line is the Čerenkov angle for muons.*

data. Also plotted in Figure 2 is the fitted distribution of vertex angles for simulated cascades from a typical AGN model, normalized to the number of events in the ≥ 1.6 PE sample. We have used the matter attenuation models of Gandhi et al. (1996) to determine the effect of earth attenuation. It is clear that the fitted events do not appear to be drawn from the cascade distribution, either in the high PE sample or the larger parent sample.

No evidence for any AGN–neutrino–induced cascades is found in our data, either from the presence of an excess above background, or from the angular distribution of the events which comprise the most likely candidates for cascades. In all cases the data are completely consistent with atmospheric cosmic–ray muon events.

Limits on AGN neutrinos

We establish the limit, plotted in Figure 3, by the 90% confidence level Poisson–statistics prescription of a maximum allowed signal flux of 2.3 counts above our estimated minimum detectable flux. This provides a limit that may be compared with the EAS-TOP limit (Aglietta et al. 1994), in which 7 events were observed with 11 expected, also consistent with background.

If we use a more conservative approach to establishing the limit, by assuming that the 17 observed events could include a possible signal (though no evidence was seen for this in event–by–event analysis) then the 90%CL limits are 2.6 times higher. However we note that this prescription is not consistent with the approach of Aglietta et al. (1994) and the limits cannot be accurately compared in this case.

Because the typical AGN neutrino model predicts that the ratio of the number of electron neutrinos to muon neutrinos (and antineutrinos) is of order 1/2, we have estimated the differential limit under this assumption.

Fig. 3: The limit derived here ("SPS limit") is plotted along with a number of neutrino models and other limits. See text for details.

In Figure 3 we also plot a number of suggested models, as well as atmospheric neutrino spectra, and limits from the underground muons observed by the Frejus collaboration (Rhode et al. 1996) and the extensive air-shower limits given by the EAS-TOP experiment (Aglietta et al 1994; 1995). The limits from the Fly's Eye (Baltrusaitas et al. 1985) apply for three different assumed cross sections for ν_e interactions in the atmosphere: $\sigma_\nu = 10^{-31}\ cm^2$ (uppermost limit), $10^{-30}\ cm^2$ (middle limit),and $10^{-29}\ cm^2$ (lowest limit). In each case the cross section is assumed constant for $10^8 \leq E_\nu \leq 10^{11}\ GeV$. The cross sections used by Baltrusaitas et al. appear to be about an order of magnitude higher than those estimated by Gandhi et al (1996).

The AGN neutrino models shown are from Szabo and Protheroe (1994; S & P in the figure), Stecker and Salamon (1995), Protheroe (1996), Biermann (1992) and are a representative sample of those available. The Frejus limits, based on measurements of horizontal muon events, appear to eliminate the highest flux models of Szabo and Protheroe (1994). Also shown here is the expected horizontal flux from atmospheric neutrinos, from Lipari (1993).

The limit at the W resonance includes the typical ratio of electron to muon neutrinos in the models and the severe attenuation of these electron neutrinos passing through the Earth.
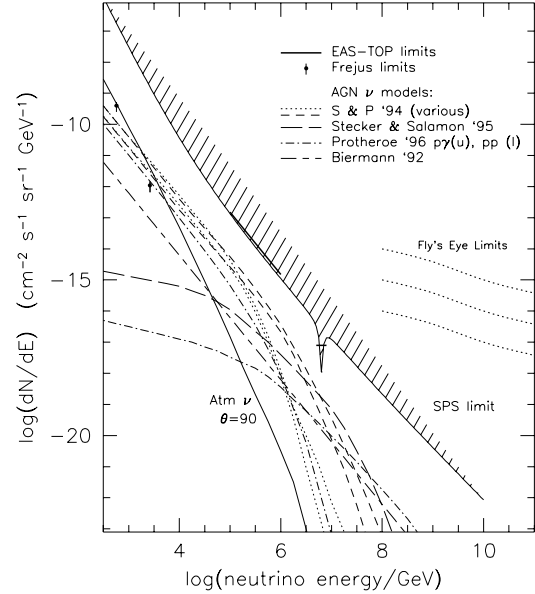
The limit at this energy is:

$$\frac{dF_\nu}{dE_\nu}(6.3\ PeV;AGN\ \nu)\ \leq 1.1\times 10^{-18}cm^{-2}s^{-1}\ sr^{-1}\ GeV^{-1}. \tag{1}$$

This is the most stringent limit at this energy and improves on the existing EAS-TOP limit by about a factor of 7.

Our value for the limit assumes that the electron neutrino+antineutrino to muon neutrino+antineutrino ratio is ~ 0.5, as most models predict, and that there is no significant particle–antiparticle asymmetry. At the resonance energy, the model–*independent* limit for anti-electron neutrinos is more stringent:

$$\frac{dF_\nu}{dE_\nu}(6.3\ PeV;mod.\ indep.)\ \leq 3.2\times 10^{-19}cm^{-2}s^{-1}\ sr^{-1}\ GeV^{-1}. \tag{2}$$

CONCLUSION

We find it quite remarkable that a modest detector can achieve such a large sensitive mass, though not designed nor optimized for this use. This instrument, intended merely as a proof-of-concept for a deep-ocean muon tracking instrument, has within less than 1 day's total livetime produced the first limits at these high energies which begin to approach the predictions of the AGN neutrino models.

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